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Assessing the environmental impact of inland waterway transport using a life-cycle assessment approach: The case of Flanders

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ABSTRACT

Focus in determining the environmental component of external transport costs has been mainly directed towards vehicle travel related emissions, while more indirect emissions related to well-to-tank operations, vehicle fleet and transport infrastructure received less attention. Especially for inland waterway transport, little research exists in this domain.

In this paper, a life-cycle assessment (LCA) based framework is recommended in order to assess the full environmental impact of inland waterway transport services. Environmental emissions (both air polluting and greenhouse gas emissions) for barge transport are analyzed in detail for one particular geographical region, namely Flanders (in Belgium), applying an LCA approach.

Three distinct categories are being considered: emissions directly related to vehicle operation (both "tank-to-wheel" and "well-to-tank" emissions), emissions related to barge fleet (building and maintenance of barges) and emissions related to transport infrastructure (construction, operation and maintenance of waterway infrastructure). This approach allows to map environmental emissions for different transport components in much greater detail and enables to determine their relative importance. The analysis also shows that for some pollutants, taking into account other categories besides vehicle travel is relevant from a sustainability perspective.

1. Introduction

Next to large economic and social benefits, transport services also cause significant, mostly negative, external costs, defined by Bickel and Friedrich (2005) as:

> "An external cost arises, when the social or economic activities of one group of persons have an impact on another group and when that impact is not fully accounted, or compensated for, by the first group."

A rather impressive list of external costs is associated with transport activities, caused by emissions (climate change effects and air pollution), accidents, noise, soil contamination, interference in the ecological system, damage to infrastructure, visual nuisance, congestion and effects associated with up and downstream processes, such as extraction, refining and transport of fuels (pre-combustion processes) and construction, maintenance and scraping of vehicles and infrastructure (Maibach et al., 2008). These external costs cause transport market prices to not fully reflect the societal cost of transport services, resulting in transport activity levels generally above social optimum. This market mechanism's failure to achieve social optimum can provide a rationale for government intervention (Schmidtchen et al., 2009). European transport policy as advocated by the European Commission proposes an internalization of external costs in order to initiate a shift from less to more sustainable transport services and achieve more socially optimal transport decisions by stakeholders (European Commission, 2011). A correct assessment of negative externalities is however a crucial but complex element in such an approach.

In this paper, the focus will be on transport related air emissions, which can be divided in two broad categories. On the one hand emission of air pollutants such as particulates (particulate matter $PM_{2,5}$ and PM_{10}), nitrogen oxide (NO_x), sulfur dioxide (SO_2), heavy metals and volatile organic compounds (VOCs). Air pollution related external costs include impacts on human health, impacts on materials and buildings, damages to agricultural crops and costs for further damage to ecosystems (biosphere, soil, water, forests). Health costs (mainly caused by particulates, emission of exhaust gases or transformation of other pollutants) are by far the most important air pollution external cost category (Maibach et al., 2008). On the other hand there are emissions of greenhouse gases (GHG) such as carbon dioxide (CO_2), nitrogen oxide (N_2O) and methane (CH_4). Social costs of climate change are described in literature as rising sea levels, modified energy use (changes in need of heating), agricultural impact, need of drinking water, health impact, ecosystems and biodiversity, extreme weather situations and increase of so-called "major events" (such as change in the Gulf current, collapse of the Amazon forest, methane explosions, and alteration of the monsoon

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season). Estimation of climate change costs is characterized by high complexity when predicting long term effects on a global scale and risk patterns which are hard to anticipate (Maibach et al., 2008).

With regard to environmental emissions of transport modes, scientific literature and policy makers still mainly focus on vehicle travel related emissions. However, in order to effectively mitigate environmental impacts from transportation modes, life-cycle environmental performance should be considered including both direct and indirect processes and services required to operate the vehicle, taking into account raw material extraction, manufacturing, construction, operation, and maintenance, and end of life of vehicles, and infrastructure and fuels (Chester & Horvath, 2009).

In order to assess full environmental sustainability of a transport service with regard to emissions, a life-cycle assessment (LCA) based methodology is therefore recommended (Chester & Horvath, 2009; Pettersen, Bergsdal, Hung, & Solli, 2011; Spielmann, Bauer, Dones, Scherrer, & Tuchshmid, 2007).

The structure of this paper comprises two main parts. First, a literature study is performed to identify current academic knowledge on transport related LCA's. Based on this literature study, an LCA-based framework is proposed to map transport related emissions. Secondly, the proposed methodology is applied to inland waterway (IWW) transport in Flanders, in order to derive specific emission factors for different GHG and air pollutants, differentiated by barge type and per waterway class, and this for different transport service components (vehicle operation, vehicle fleet and transport infrastructure). In this way, relative importance of the different components can be compared on different dimensions (e.g. for different pollutants, for different barge types, for different waterway classes) and environmental impact of IWW transport related emissions can be assessed in much greater detail. To finish, conclusions and further research goals are formulated.

2. Transport related life-cycle assessments

This section consists of three parts. Firstly, background and theoretical concept of life-cycle assessment is shortly described. Secondly, scientific literature with regard to transport related life-cycle assessments is summarized. Thirdly, findings from literature that are relevant for applying an LCA-based framework to map emissions of transport services are identified and a framework to map the emissions of a transport service is discussed.

2.1. Life-cycle assessment: background and theoretical concept

Frischknecht (1998) defines life cycle assessment (LCA) as a method for analysis and assessment of potential environmental impacts along the life cycle of a good or a service. An LCA is, according to Frischknecht (1998)

> "[…] applicable on products, processes or firms, to document their environmental performance, to identify potentials for environmental improvements, to compare alternative options as well as to substantiate ecolabelling criteria."

LCA takes into account a product's full life cycle from extraction of resources, through production, use and recycling, up to disposal of remaining waste (Institute for Environment & Sustainability, 2010). Life cycle assessment is therefore considered to be a vital and powerful decision support tool, complementing other methods, which are equally necessary to help effectively and efficiently make consumption and production more sustainable (Institute for Environment & Sustainability, 2010).

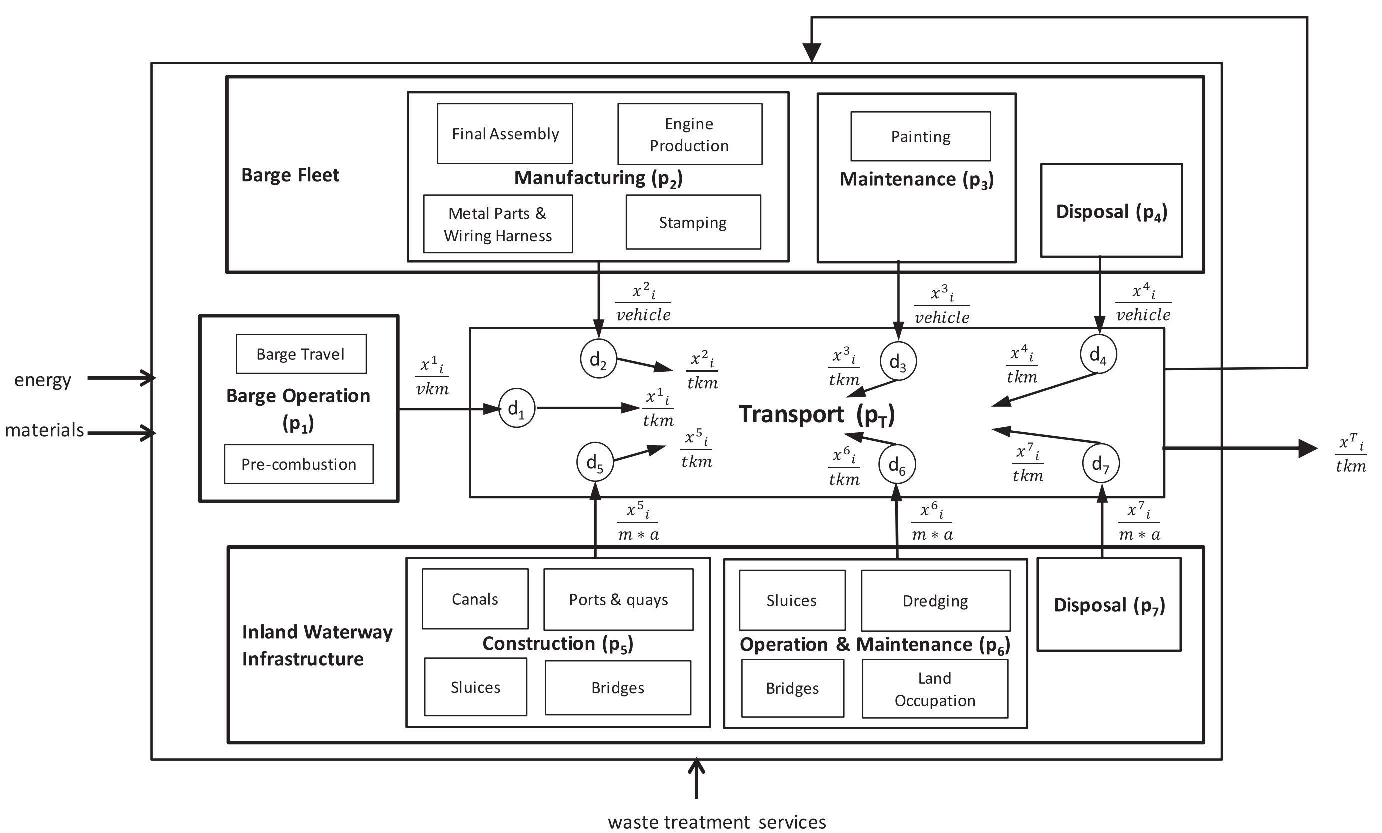

Fig. 1. Life cycle inventory of inland waterway transport (own setup based on Spielmann & Scholz, 2004).

In order to create a methodological framework for practical application of LCAs and to ensure that all requirements of the methodologies are met, the International Standardization Organization (ISO) has published two standards: ISO 14040 (European Committee for Standardization, 2006a) and ISO 14044 (European Committee for Standardization, 2006b).

According to ISO standards, an LCA study consists of four phases: goal and scope definition phase, inventory analysis phase, impact assessment phase and interpretation phase (European Committee for Standardization, 2006a). A clear initial goal definition is essential for a correct later interpretation of results. During the scope definition phase the object of the LCA study is identified and defined in detail. The main part of this phase is to derive requirements on methodology, quality, reporting and review in accordance with the goal of the study (Institute for Environment & Sustainability, 2010). During the life cycle inventory (LCI) phase actual data collection and modeling of the system is carried out, in line with goal definition and requirements set in the scope phase. Life cycle impact assessment (LCIA) is the phase where inputs and outputs of elementary flows collected and reported in the LCI phase are translated into impact indicator results related to human health, natural environment, and resource depletion. In the interpretation phase, results of LCIA are appraised in order to answer questions posed in the goal definition and to develop recommendations (Institute for Environment & Sustainability, 2010).

2.2. Transport related LCAs: literature review

With regard to transport services, an LCA takes into account not only emissions directly associated with vehicle operation, but also emissions related with all other aspects required to facilitate the transport service, making it a valuable approach to analyze exactly how transport modes perform environmentally. Therefore, LCA methodology has already been applied in a variety of cases in the field of transport. Below, scientific literature related to LCAs will be discussed for, first, passenger transport, and, second, freight transport.

2.2.1. Passenger transport

Chester and Horvath (2009) presented results of a comprehensive life-cycle energy, GHG emissions, and air pollutant emission inventory for automobiles, buses, trains, and airplanes in the US, including vehicles, infrastructure, fuel production, and supply chains. Using a methodology of hybrid LCA in combination with an input/output-analysis, total life-cycle energy inputs and GHG emissions were found to contribute an additional 63% for road, 155% for rail, and 31% for air systems over vehicle tailpipe operation. For air pollutants, vehicle non-operational components were found to often dominate total emissions, with life-cycle air pollutant emissions between 1.1 and 800 times larger than vehicle operation. Relative performance of modes was found to be highly sensitive to ranges of passenger occupancy.

In 2010, Chester and Horvath added an LCA for high-speed rail in California, again stressing the importance of assumed level of ridership when comparing modes (Chester and Horvath, 2010). Also other papers have focused on high-speed rail LCA. Rozycki, Koeser, and Schwarz (2003) developed an ecology profile for German high-speed rail passenger transport system. Tuchschmid (2009) developed a methodology to account for infrastructure of European high-speed passenger traffic (e.g. TGV-lines in France or AVE-network in Spain) in carbon footprint calculation, taking into account components of operation, rolling stock and track system and found that infrastructure share in carbon footprint of high-speed rail ranges for different situations of average European network between 31% and 85%, depending on electricity mix, traffic on rail network and share of bridges and tunnels (Tuchschmid, 2009). Pettersen et al. (2011) performed life cycle management projects with regard to infrastructure development and operation of high-speed rail in Norway, confirming the importance of infrastructure, in most cases representing half or more of total GHG emissions.

In the Belgian CLEVER (Clean Vehicle Research: LCA and policy measures) project an extensive LCA was performed by the complete Belgian passenger car fleet (Van Mierlo et al., 2011). Also recently, Hawkins, Singh, Majeau-Bettez, and Strømman (2012) developed a life cycle inventory of conventional and electric vehicles in order to assess environmental sustainability over a range of impact categories.

2.2.2. Freight transport

The amount of published LCA studies on freight transport modes is rather limited. Some two decades ago, Eriksson, Blinge, and Lövgren (1996) studied the road transport sector with a life-cycle perspective by collecting detailed data on environmental burdens caused by different transportation activities such as fuel production, fuel combustion at driving, maintenance of the vehicle and production and after use treatment of the vehicle. Production, maintenance and after use treatment of vehicles were found to contribute significantly to total environmental impact of road transportation, measured per vehicle kilometer. Infrastructure related emissions were not considered. More recently, Facanha and Horvath (2007) analyzed life-cycle air emission factors associated with road, rail and air transportation of freight in the United States, taking into account all life-cycle phases of vehicles, infrastructure and fuels in a hybrid life-cycle assessment. Based on their calculations total lifecycle emissions of freight transportation modes are concluded to be underestimated if only tailpipe emissions are accounted for. For CO_2 and NO_x, tailpipe emissions underestimate total emissions by up to 38% depending on the mode, while for CO and SO_2 total life-cycle emissions are even calculated to be up to seven times higher than tailpipe emissions. IWW transport was however not considered.

Spielmann and Scholz (2005) indicate that comprehensive LCIs of various modes of transport are available from Frischknecht et al. (1996) and Maibach et al. (1999). Frischknecht et al. (2005) updated and harmonized these LCI's within the ecoinvent 2000 project framework. The ecoinvent database was created by Swiss Centre for Life Cycle Inventories and is a joint initiative of several universities and institutes of Switzerland with the support of several Swiss Federal Offices. The ecoinvent database is a continuously evolving reference work for life cycle inventory data covering areas of energy, building materials, metals, chemicals, paper and cardboard, forestry, agriculture, detergents,

Table 1
Barge type characteristics applied in EMMOSS (Vanherle et al., 2007).

Ship type	Name	Distribution (engine age)	Length (m)	Width (m)	Unloaded draft (m)	Loaded draft (m)	Power class [indicative] (kW)	Load capacity (ton)
M0	Small motorship	L	35	4,5	0,4	2,2	70	< = 250
M1	Spits-Péniche	L	38,5	5,05	0,5	2,5	250	251–400
M2	Kempenaar-Campinois	L	55	6,6	0,6	2,5	250	401–650
M3	Dutch barge-Hagenaar	L	67	7,2	0,7	2,5	1000	651–800
M4	D.E.K. (Dortmund-Ems Canal)	M	67	8,2	0,7	2,7	1000	801–1050
M5	Extended D.E.K.	M	80	8,2	0,7	2,7	1000	1051–1250
M6	R.H.K. (Rhine–Herne-Canal)	S	85	9,5	0,8	2,9	1000	1251–1750
M7	Extended R.H.K.	S	105	9,5	0,8	3,0	1000	1751–2050
M8	Big Rhine barge	S	110	11,4	0,8	3,5	1300	>2050

Table 2
2010 emission factors for barge travel in g/tkm: loaded M4 type barge on canal Brussels–Scheldt (own calculations based on EMMOSS data provided by VMM & TML, 2012).

Barge type	NH_3	SO_2	CO_2	CO	NO_x	Methaan	TSP	VOC	NMVOC	N_2O	$PM_{2,5}$	PM_{10}
M4	1,18E−04	2,36E−02	3,69E+01	1,02E−01	5,26E−01	8,73E−04	1,83E−02	2,18E−02	2,09E−02	9,43E−04	1,65E−02	1,74E−02

transport services and waste treatment (Frischknecht et al., 2005). General modeling principles and structure of the ecoinvent-datasets are well documented and background information for each of the 4000 covered processes is provided in reports (Tuchschmid, 2009). Quality guidelines, established in order to ensure coherent data acquisition and reporting across the various institutes involved, are described in Frischknecht and Rebitzer (2005).

Transport services receive particular attention within ecoinvent. In order to account for cumulative exchanges due to transportation occurring between two process steps of a product system, generic background data representing average transport conditions in Switzerland and Europe is generated for four modes of transport (air, rail, road and water transport). Three components of environmental interventions are considered per transport service: vehicle operation (including vehicle travel), vehicle fleet, and transport infrastructure; detailed information on transport services and background data for transport in ecoinvent can be found in Spielmann and Scholz (2005) and Spielmann et al., 2007.

Based on average operation and infrastructure characteristics, Spielmann and Scholz (2005) conclude that for gaseous emissions, freight transport by IWW and rail show 65% to 92% lower cumulative emissions than road transport. They also stress that, although vehicle travel remains the most important category for a number of pollutants, the picture is much more mixed for other emissions such as NMVOCs, PM and heavy metals, with important relative shares for precombustion and infrastructure related processes.

2.3. LCA-based framework for barge transport

Since general modeling principles and structure of ecoinvent-datasets are considered to be scientifically solid and transparent, modeling of barge transport in this paper will be based on the ecoinvent transport service framework. The framework for IWW transport presented in Fig. 1 is therefore based on the framework provided by Spielmann and Scholz (2005) for road transport.

Ecoinvent modeling of "water transport" is divided into three components (Spielmann et al., 2007).

1. Vessel operation: all processes directly connected with barge operation, distinguishing between exchanges linked to vessel travel and exchanges related with upstream pre-combustion processes. Ecoinvent distinguishes between "barge" and "barge tanker" vessel types and assumes exclusive use of diesel for propelling. Distinction is made between fuel content dependent emissions (SO_2) and combustion process dependent emissions (NO_x, CO, HC, N_20).
2. Vessel fleet: all processes describing vessel life cycle (excluding the operation), such as construction, maintenance and disposal of vessels. Ecoinvent assumes an average barge capacity of 1.000 t/vessel and barge tanker capacity of 1.200 t/vessel.
3. Port infrastructure: all processes comprising port infrastructure life cycle, including port construction, operation and maintenance as well as disposal. For inland shipping, artificial waterway construction and operation are modeled. Since port infrastructure data is based on seaports and thus is applicable for maritime water transport, only artificial waterway construction and operation datasets in ecoinvent are relevant for barge transport (Spielmann et al., 2007).

A critical assumption in ecoinvent v2.1 is that all material and service inputs are modeled with production and service standards from 2000, even if e.g. canal construction is situated in a further past. Material and energy consumption due to maintenance activities are taken into account. For vessels, the disposal of bulk materials is also taken into account, whereas for canal infrastructure this is neglected due to the long life-span. Additional material and energy expenditures e.g. for the production of machinery are neglected in ecoinvent.

Transport datasets in ecoinvent are primarily designed to provide background data for straightforward application in a variety of life cycle studies, and are therefore mainly intended to allow for a preliminary screening of the importance of transport processes within a product life

Table 3
Related emissions for selected ecoinvent processes (Own calculations, based on ecoinvent v2.2, 2012).

Name	Unit	Diesel, at refinery	Diesel, at regional storage	Barge	Barge tanker	Maintenance, barge	Canal	Maintenance, operation, canal
Unit		kg	kg	Unit	Unit	Unit	ma	ma
GHGs								
Carbon dioxide (CO_2)	kg	4,41E−1	4,67E−1	7,88E+05	9,45E+05	1,23E+05	5,62E+01	1,82E+00
Dinitrogen monoxide (N_2O)	kg	8,02E−06	8,80E−06	1,42E+01	1,70E+01	3,12E+01	3,49E−04	5,40E−05
Methane (CH4)	kg	1,85E−03	1,88E−03	1,61E+03	1,94E+03	3,55E+02	7,38E−02	3,06E−03
Ammonia (NH3)	kg	5,82E−06	8,75E−06	3,21E+01	3,85E + 01	2,40E+01	2,18E−03	2,48E−05
Sulfur dioxide (SO2)	kg	4,22E−03	4,33E−03	3,07E+03	3,68E+03	5,51E+02	5,51E−02	5,83E−03
Cadmium (Cd)	kg	4,52E−08	4,60E−08	2,62E−01	3,15E−01	7,70E−03	1,35E−06	3,49E−08
Chromium (Cr)	kg	1,00E−07	1,15E−07	3,51E+00	4,21E+00	2,02E−01	2,11E−05	3,31E−07
Copper (Cu)	kg	1,29E−07	1,48E−07	1,82E+00	2,18E+00	1,09E−01	2,06E−05	5,41E−07
Nickel (Ni)	kg	6,72E−07	7,02E−07	3,44E+00	4,12E+00	1,49E−01	1,65E−05	9,35E−07
Lead (Pb)	kg	1,42E−07	1,58E−07	2,47E+00	2,96E+00	7,50E−02	4,27E−05	5,43E−07
Zinc (Zn)	kg	2,18E−07	2,76E−07	4,32E+00	5,18E+00	1,55E−01	1,08E−04	7,63E−07
Particulates <2,5 um (PM2,5)	kg	1,63E−04	1,72E−04	4,54E +02	5,45E+02	2,41E+01	1,30E−02	4,43E−04
Particulates >2,5 um and <10 um	kg	4,73E−05	5,46E−05	8,03E+02	9,63E+02	6,09E+01	2,59E−02	1,10E−04
Particulates >10 um	kg	1,27E−04	1,44E−04	1,32E+03	1,58E+03	3,89E+01	4,68E−02	1,14E−03
Particulates <10 um (PM10)	kg	2,10E−04	2,27E−04	1,26E+03	1,51E+03	8,50E+01	3,88E−02	5,54E−04
Total particulates (TSP)	kg	3,37E−04	3,70E−04	2,58E+03	3,09E+03	1,24E+02	8,56E−02	1,69E−03
Carbon monoxide (CO)	kg	6,79E−04	7,34E−04	6,68E+03	8,02E+03	1,75E+02	2,36E−01	5,64E−04
Nitrogen Oxides (Nox)	kg	1,65E−03	1,78E−03	1,58E+03	1,89E+03	3,41E+02	1,23E−01	2,99E−03
NMVOC (via ecoinvent)	kg	1,18E−03	1,19E−03	1,27E+03	1,52E+03	1,60E+04	1,89E−02	2,28E−04

Table 4
2010 emission factors for precombustion in g/tkm: loaded M4 type barge on canal Brussels–Scheldt (own calculations based on ecoinvent data, 2012 and EMMOSS data provided by VMM & TML, 2012).

Barge type	NH_3	SO_2	CO_2	CO	NO_x	Methaan	TSP	VOC	NMVOC	N_2O	$PM_{2,5}$	PM_{10}
M4	1,73E−04	1,02E−01	1,08E+01	1,68E−02	4,09E−02	4,44E−02	8,42E−03	2,93E−02	2,82E−02	2,00E−04	3,99E−03	5,20E−03

Table 5
Emissions related to barge construction for M4 barge type in kg (own calculations based on ecoinvent data, 2012).

Barge type	NH_3	SO_2	CO_2	CO	Nox	Methaan	TSP	VOC	NMVOC	N_2O	$PM_{2,5}$	PM_{10}
M4	3,33E+01	3,18E+03	8,17E+05	6,94E+03	1,63E+03	1,68E+03	2,67E+03	1,37E+03	1,32E+03	1,47E+01	4,72E+02	1,30E+03

cycle (Spielmann & Scholz, 2005). Spielmann et al. (2007) therefore state that:

> "For transport-focused LCA the presented generic datasets may have to be replaced with more specific data."

Integration of more case-specific data for IWW transport in Flanders building on the ecoinvent transport service framework will be the focus of the next section. Since the main goal is to map environmental air emissions for IWW transport in detail for different components and to determine their relative importance, focus will be on inventory analysis phase of LCA and thus construction of IWW transport related life cycle inventory (LCI).

3. LCI for inland waterway transport related emissions in Flanders

In this section, focus is on analyzing in detail environmental emissions, for one particular transport mode, namely inland waterway transport, for one particular geographical region, namely Flanders (in Belgium), by integrating case-specific, regional data for IWW transport in Flanders based on the ecoinvent transport service framework. Analysis includes CO_2, CO, NO_x, SO_2, NH_3, N_2O, CH_4, VOC, NMVOC, TSP, $PM_{2,5}$ and PM_{10}. Structure in this section is based on the three components described in the ecoinvent modeling of the "water transport" process: barge operation, barge fleet and IWW infrastructure. But first, a literature study was performed to identify available case-specific regional emission data related to IWW transport in Flanders to be applied in the framework.

3.1. Literature study: inland waterway transport related emissions for Flanders

The goal was to identify emission factors published in literature that were relevant and applicable for IWW transport in Flanders. The following studies and models were analyzed: TREMOVE (De Ceuster et al., 2007), VITO (De Vlieger, Cornelis, Joul, & Int Panis, 2004), STREAM (den Boer, Otten, & van Essen, 2011), Royal Haskoning (Schilperoord, 2004), Environ (Lindhjem, 2004), INFRAS (Schreyer et al., 2004), ADEME (2006), EcoTransIT (Knörr, Seum, Schmied, Kutzner, & Anthes, 2010), EMMOSS (Vanherle, Van Zeebroeck, & Hulskotte, 2007), EMS (Ministerie van Verkeer en Waterstaat, 2003) and Arcadis (Franckx, Vanhove, & Schoukens, 2011).

Based on an in-depth analysis it was concluded that the EMMOSS model (Vanherle et al., 2007), developed by Transport & Mobility Leuven (TML) for the Flemish Environmental Agency (VMM), is best suited to provide barge travel related emission factors. EMMOSS has a solid scientific basis and uses a detailed bottom-up approach to determine operational tank-to-wheel related emissions for a wide variety of pollutants for both ship (barge as well as maritime) and rail transports in a Flemish context. For IWW transport, the model differentiates between 30 different barge types, taking into account engine age structure of barges using a Weibull distribution, and identifies 9 waterway types, including 6 CEMT classes (I–VI) [1] and 3 river classes, taking into account maximum speed per barge type per waterway. Operational energy usage by barges in EMMOSS takes into account ship characteristics (length, width, hull shape), waterway characteristics (width, depth, current) and transported volume (load rate, empty trips). EMOSS, however, was built to map overall total direct emissions of rail and water transport in Flanders and thus emission factors expressed in tonkilometers are not direct outputs of the model. Based on outputs of the model provided by VMM, together with underlying assumptions for load factors, engine age and canal characteristics, recalculations were nevertheless possible to derive emission factors in tonkilometer for the different pollutants, differentiated per ship type and per waterway class. These emission factors will be used to model barge travel related operational emissions in the LCA framework. The focus in this paper will be on M-type barges as classified in EMMOSS (Table 1).

With regard to barge fleet or IWW infrastructure related emission data, little or no applicable data was found in the literature review, confirming the need for an LCA based approach.

Next, emission factors for the different components will be discussed in detail.

3.2. Barge operation

3.2.1. Barge travel

This component comprises fuel combustion related emissions that occur during operational barge travel (tank-to-propeller emissions). EMMOSS output values expressed in ton pollutant for specific waterways are used as a basis for recalculating emission factors expressed per tonkilometer per barge type per waterway class. A selection was made of waterways that were considered to be representative for the most common canal and river types in Flanders.[2] Transport performance figures per individual waterway expressed in tonkilometer required for recalculation were provided by Waterwegen en Zeekanaal NV. Average load rates of barges on selected canals were provided by EMMOSS.[3]

As an example, Table 2 shows specific emission factors for barge travel with a loaded M4 type barge with a load rate of 68% on the canal Brussels–Scheldt for 2010.

Calculations for other barge types revealed that, not surprisingly, larger ships are generally more environmentally friendly during travel

[1] The Classification of European Inland Waterways is a set of standards for interoperability of large navigable waterways forming part of the Trans-European Inland Waterway network within Continental Europe and Russia, created by ECMT Resolution 92/2 on New Classification of Inland Waterways (Conférence Européenne des ministres des Transports (CEMT), 1992). These classification dimensions, which take into account the dimensions of the structures including the locks and boat lifts on the route, are also referred to as CEMT Classes I–VII.

[2] Albert canal (CEMT VI), Brussels–Scheldt canal (CEMT VI), the upper Scheldt river (CEMT V), Roeselare–Leie canal (CEMT V), Ghent–Bruges canal (CEMT IV) and Leuven–Dijle canal (CEMT II).

[3] EMMOSS load rates for selected waterways: Albert canal (0,765), Brussels–Scheldt canal (0,676), the upper Scheldt river (0,685), Roeselare–Leie canal (0,808), Ghent–Bruges canal (0,614) and Leuven–Dijle canal (0,769).

Table 6
Emission factors for barge construction in g/tkm for M4 barge (based on ecoinvent data, 2012).

Barge type	NH_3	SO_2	CO_2	CO	NO_x	Methaan	TSP	VOC	NMVOC	N_2O	$PM_{2,5}$	PM_{10}
M4	3,94E−05	3,76E−03	9,67E−01	8,21E−03	1,93E−03	1,98E−03	3,16E−03	1,62E−03	1,56E−03	1,74E−05	5,58E−04	1,54E−03

Table 7
Emission factors for barge maintenance in g/tkm for M4 barge (based on ecoinvent data, 2012).

Barge type	NH_3	SO_2	CO_2	CO	NO_x	Methaan	TSP	VOC	NMVOC	N_2O	$PM_{2,5}$	PM_{10}
M4	2,72E−05	6,25E−04	1,39E−01	1,99E−04	3,87E−04	4,03E−04	1,41E−04	1,89E−02	1,81E−02	3,54E−05	2,73E−05	9,64E−05

due to scale effects, however between consecutive classes differences can be small or even more favorable for smaller barge types (e.g. between M3 and M4). This might be due to assumed age distribution of engines per barge type, fuel efficiency differences between barges and/or use of an average loading rate per waterway which might not reflect existing differences in loading rates between barge types on a specific waterway.

3.2.2. Pre-combustion

This component comprises emissions indirectly linked to the operational use of barges, namely those that occur during exploring, refining, transporting and storing of fuels that are eventually used during barge travel (well-to-tank emissions). No directly applicable emission factors for precombustion were available in literature, therefore data from ecoinvent processes “diesel, at refinery” and “diesel, at regional storage” are used. Exploration related emissions are not included, due to uncertainty regarding fuel origin. Ecoinvent process “diesel at refinery” includes all processes on the refinery site excluding emissions from combustion facilities, including waste water treatment, process emissions and direct discharges to rivers, while ecoinvent process “diesel, at regional storage” includes transportation of product from refinery to the end user, operation of storage tanks and petrol stations and emissions from evaporation and treatment of effluents. Ecoinvent datasets provide resources used for refining and storing of 1 kg of diesel (e.g. 0,0146 kg water, various chemicals, different variants of crude oil as well as energy and transport demand for refining 1 kg of diesel).

Table 3 in turn shows resulting emissions calculated from ecoinvent databases for selected ecoinvent processes relevant for inland waterway transport. The table states for example that 0,441 kg CO_2 will be emitted during refining of 1 kg diesel.

Barge travel fuel consumption per barge type can be deducted directly from CO_2-emissions generated in EMMOSS (with conversion factor of 3.100 g CO_2 per 1 kg diesel). When combining resulting fuel consumption with ecoinvent pre-combustion emissions of Table 3, emission factors related to precombustion can be calculated for selected waterways. Table 4 shows resulting emission factors for precombustion processes for barge travel with a loaded M4 type barge (again with a load rate of 68%) on the canal Brussels–Scheldt for 2010.

Also for other barge types, calculations were made. Similar conclusions apply here as for barge travel when comparing different barge types.

3.3. Barge fleet

3.3.1. Barge manufacturing

This component comprises the emissions associated with construction of barges. Two approaches can be proposed: a more straightforward approach starting from processes “barge” and “barge tanker” available in ecoinvent database and applying the emission factors proportionally depending on dimensions of different barge types, or a more refined approach using specific data related to materials, transport and energy used in construction of different barge types and applying the emission factors of relevant ecoinvent subprocesses (for i.e. “reinforcing steel, at plant”, “chromium steel 18/8, at plant”, “synthetic rubber at plant”, “alkyd paint, white, 60% in solvent, at plant”, “glued laminated timber, for outdoor use, at plant”, and “transport, lorry >16 t, fleet average”) in order to make a detailed calculation. However, barge construction data differentiated per barge type is currently unavailable, so only the first approach was feasible. The second approach however is more accurate and advisable for specific case studies.

For exchanges related to processes “barge” and “barge tanker” manufacturing, ecoinvent assumes an average barge capacity of 1.000 t/vessel and barge tanker capacity of 1.200 t/vessel, which corresponds to an M4 barge (D.E.K. barge). Resulting emissions associated with processes “barge” and “barge tanker” are shown in Table 3 (e.g. 788.000 kg CO_2 and 454 kg $PM_{2.5}$ will be emitted during construction of one barge with a load capacity of 1.000 t).

In order to calculate average emissions for an M4 barge type, a proportional division of 81% barges versus 19% barge tankers was assumed for the Belgian inland waterway fleet (based on 2011 data from the Institute for Transport along Inland Waterways), resulting in average emissions for an M4 barge as presented in Table 5.

For other barge types, resources listed in ecoinvent can be recalculated proportionally based on dimensions presented in Table 1, since the product of length, width and loaded draft can be used as a proxy for volume of a barge type. Resources are then assumed to be used in proportion to the volume of the ship, with M4 serving as base type. As a result, construction of a larger barge type will result in larger overall emissions compared to a smaller barge type, and this in proportion to their dimensions. However, to calculate emission factors per tonkilometer, data is needed on transport performance over the life-time of a barge, expressed in tonkilometers. This data is provided in ecoinvent for an M4 barge (738.644.684 t km for barge and 881.119.408 t km for barge tanker), but similar data for other barge types is not available in literature. Therefore, same emission factors in tonkilometer are applied for all different barge types, under the assumption that the larger absolute emissions for larger barge types are exactly compensated by relatively higher tonkilometers over their life-time due to scale effects. However, it can be expected that scale effects overcompensate the larger emissions in absolute figures in case of larger barge types, but current lack of specific transport performance data per barge type in Flanders does not allow to incorporate this effect into the calculations. Further research and data collection would be needed to resolve this issue. For the time being, emission

Table 8
Waterway dimensions for selected waterways (own setup based on data from Promotie Binnenvaart Vlaanderen, 2012).

	Waterway dimensions		
Waterway	Length (m)	Average width (m)	Average depth (m)
Upper Scheldt	50.014	5,3	2,5
Canal Ghent–Bruges	39.739	46,0	4,1
Canal Leuven–Dijle	30.034	28,0	2,7
Canal Roeselare–Leie	16.512	55,0	5,3
Canal Brussels–Scheldt*	27.000	55,0	6,0
Albert Canal	129.577	86,0	5,0
Main-Donau Canal	171.000	42,0	4,0

Table 9
Emissions related to canal construction per selected waterway in kg per meter*year (own calculations based on ecoinvent data, 2012).

Waterway	NH_3	SO_2	CO_2	CO	NO_x	Methaan	TSP	VOC	NMVOC (kg/ma)	N_2O	$PM_{2,5}$	PM_{10}
Ecoinvent (Main-Donau)	2,18E−03	5,51E−02	5,62E+01	2,36E−01	1,23E−01	7,38E−02	8,56E−02	1,97E−02	1,89E−02	3,49E−04	1,30E−02	3,88E−02
Canal Brussels–Scheldt	4,29E−03	1,08E−01	1,10E+02	4,64E−01	2,42E−01	1,45E−01	1,68E−01	3,87E−02	3,72E−02	6,85E−04	2,54E−02	7,63E−02
Albert Canal	5,59E−03	1,41E−01	1,44E+02	6,05E−01	3,16E−01	1,89E−01	2,19E−01	5,05E−02	4,84E−02	8,93E−04	3,32E−02	9,94E−02

Table 10
2010 emission factors for canal construction in g/tkm on selected waterways (own calculations based on EMMOSS data provided by VMM & TML, 2012).

Waterway	NH_3	SO_2	CO_2	CO	NO_x	Methaan	TSP	VOC	NMVOC (kg/ma)	N_2O	$PM_{2,5}$	PM_{10}
Ecoinvent (Main-Donau)	5,07E−04	1,28E−02	1,31E+01	5,50E−02	2,87E−02	1,72E−02	1,99E−02	4,58E−03	4,40E−03	8,11E−05	3,01E−03	9,03E−03
Canal Brussels–Scheldt	2,36E−04	5,96E−03	6,07E+00	2,55E−02	1,33E−02	7,98E−03	9,25E−03	2,13E−03	2,04E−03	3,77E−05	1,40E−03	4,20E−03
Albert Canal	1,20E−04	3,03E−03	3,09E+00	1,30E−02	6,78E−03	4,06E−03	4,70E−03	1,08E−03	1,04E−03	1,92E−05	7,12E−04	2,14E−03

factors per tonkilometer related to construction of a M4 barge, as presented in Table 6, are applied to other barge types.

3.3.2. Barge maintenance

This component comprises emissions linked to maintenance of barges. Again, two approaches similar to the ones described for barge manufacturing can be applied, namely a straightforward calculation based on ecoinvent process “barge maintenance”, or a more refined calculation based on specific data regarding materials, transport and energy used in maintenance of different barge types, and using appropriate ecoinvent subprocesses. Again, unavailability of specific data related to barge maintenance of different barge classes obliges to apply the more straightforward approach.

Ecoinvent process “barge maintenance” assumes that a barge is painted 10 times during a life-time of 40 years. The consumption of lubricates is assumed to be included in the fuel consumption for vessel operation. So next to some road and rail transports, the main resource consumed during maintenance of one unit “barge” modeled in ecoinvent is 43.600 kg alkyd white paint (with 60% solvent).[4] Resulting emissions associated with barge maintenance are shown in Table 3. For example, 123.000 kg CO_2 will be emitted during maintenance of one barge with a load capacity of 1.000 t. Noteworthy is the high amount of NMVOC, namely 16.000 kg.

Recalculation for other barge types can be done in a similar way as for barge construction, namely proportionally based on dimensions presented in Table 1. Again however, lack of transport performance data over life-time per barge type prohibits a differentiated recalculation per tonkilometer, so also here emission factors per tonkilometer related to maintenance of a M4 barge are applied to other barge types (Table 7).

3.4. Inland waterway infrastructure

3.4.1. Inland waterway construction

Distinction should be made between artificial waterways (canals) and natural waterways (rivers and lakes). Only the first category is relevant from a construction perspective. Similarly as above, two approaches are possible: a straightforward approach starting from process “canal” and applying emission factors proportionally depending on dimensions of the different canals, or a more refined approach using specific data related to materials, transport and energy used in construction of specific canals and applying emission factors of relevant ecoinvent subprocesses (such as “excavation, skid-steer loader”, “concrete, exacting, at plant”, and “reinforcing steel, at plant”). Data for ecoinvent process “canal” is derived from the Main-Donau canal in Germany, characterized by a width of 42 m (with an additional 10 m at each edge modeled as road traffic area) and an average depth of 4 m. Bridges are not included in the modeling, resulting in an underestimation of canal construction related emissions with this approach as compared to the approach used in e.g. Tuchschmid (2009) for high speed rail transport.

The second approach allows to incorporate canal-specific elements in detail (building of bridges, locks, etc.) in function of the local topography. Specific canal construction data allowing such a detailed calculation was however only partially available for one M2 type canal (canal Leuven-Dijle). Due to unavailability of construction data for other canals however, the first approach was applied for the six selected Flemish canals.

The allocation of infrastructure processes to actual transport performance expressed in tonkilometer is complex. We use the static approach applied in ecoinvent, where first material and energy expenditures for the entire transport infrastructure network are determined and a certain lifespan for the infrastructure is assumed, allowing an annual average consumption to be calculated, and second current performance figures (which are assumed to represent an average for the past and future situation) are used to link infrastructure processes to the functional unit of one tonkilometer.

Ecoinvent assumes that 4,03 m3 of ground has to be excavated and 0,31 m3 of concrete, 8,68 kg of reinforced steel and 0,0087 kg of bitumen are required for the construction of 1 m*year (ma) of canal. Lifetime of canals is assumed to be 118 years (Spielmann et al., 2007). Corresponding emissions related to construction of 1 m*year of canal of above dimensions are presented in Table 3. To derive total canal construction emissions for a specific canal, these values have to be multiplied with 118 years and total length of the selected canal.

For other canals, used resources for the Main-Donau canal are recalculated proportionally based on canal dimensions for the selected canals, presented in Table 8.

Emissions expressed in kg per meter*year for selected waterways are shown in Table 9. Ecoinvent model emissions that would have been emitted if canals would have been built with current technology and assuming a lifetime of 118 years. Some of these canals however have been excavated centuries ago before the industrialization age, and amply surpass a lifetime of 118 years. Therefore, only canal construction emissions for more recently excavated or enlarged canals are relevant and presented in Table 9. However, values in Table 9 are only indicative as they assume that these Flemish canals have been built requiring the same effort per meter*year as the construction of the Main-Donau canal, which over its length of 171 km through a rather hilly topography has to overcome a height difference in absolute terms of 233 m through 16 locks. This assumption seems more valid for the Albert Canal, which has six locks over its length of 129,5 km to overcome a height difference of 56 m between Antwerp and Liège, but also required the excavation of a 60 m deep gap through a plateau between Kanne and Ternaaien in order to avoid building locks between

[4] Ecoinvent does not take any cleaning product into account which are potentially used in addition to the paint. This might imply an underestimation of the emissions which are associated with barge maintenance that is however difficult to estimate.

Table 11
2010 emission factors for waterway maintenance and operation in g/tkm on selected waterways (Own calculations based on EMMOSS data provided by VMM & TML, 2012).

Waterway	NH_3	SO_2	CO_2	CO	NO_x	Methaan	TSP	VOC	NMVOC (kg/ma)	N_2O	$PM_{2,5}$	PM_{10}
Ecoinvent (Main-Donau)	5,77E−06	1,35E−03	4,24E−01	1,31E−04	6,96E−04	7,12E−04	3,93E−04	5,52E−05	5,30E−05	1,26E−05	1,03E−04	1,29E−04
Canal Ghent–Bruges	1,08E−07	2,52E−05	7,90E−03	2,44E−06	1,30E−05	1,33E−05	7,32E−06	1,03E−06	9,86E−07	2,34E−07	1,92E−06	2,40E−06
Canal Leuven–Dijle	4,65E−06	1,09E−03	3,42E−01	1,06E−04	5,61E−04	5,74E−04	3,17E−04	4,45E−05	4,27E−05	1,01E−05	8,31E−05	1,04E−04
Canal Roeselare–Leie	2,11E−05	4,96E−03	1,55E+00	4,80E−04	2,55E−03	2,60E−03	1,44E−03	2,02E−04	1,94E−04	4,59E−05	3,77E−04	4,71E−04
Canal Brussels–Scheldt	8,26E−06	1,94E−03	6,07E−01	1,88E−04	9,97E−04	1,02E−03	5,62E−04	7,90E−05	7,58E−05	1,80E−05	1,48E−04	1,84E−04
Albert canal	2,68E−06	6,29E−04	1,97E−01	6,09E−05	3,24E−04	3,31E−04	1,82E−04	2,56E−05	2,46E−05	5,83E−06	4,79E−05	5,98E−05

Genk and Liège. The Canal Brussels–Scheldt has to overcome a height difference of only 14 m over a distance of 20 km through 4 locks, so it has more locks per km canal than the Main-Donau canal, but a lower height difference per lock.[5] As more detailed data is lacking regarding the construction of the Flemish canals, the values for the Main-Donau canal are therefore used proportionally to the canal dimensions, but one has to keep in mind that this might potentially overestimate the emissions related to the construction of the canal Brussels–Scheldt.

In order to recalculate emissions on a tonkilometer base, data with regard to specific transport demand per waterway is needed, expressed in ((m*a)/tkm). Ecoinvent assumes a specific canal demand of 2,33E−04(m*a)/tkm for the Main-Donau canal (Spielmann et al., 2007). Specific canal demand data for selected Flemish waterways was derived based on statistics from inland waterway administrating bodies Waterwegen en Zeekanaal NV and NV Scheepvaart (1,23E−04 canal Brussels–Scheldt and 4,79E−05 for Albert canal).

Since waterways provide other functions in addition to enabling and promoting barge transport, such as functions related to recreation, water management, environment and energy, only a portion of canal construction emissions should be assigned to barge transport. Financial data from Waterwegen en Zeekanaal NV indicate that almost 45% of expenses related to waterway management in Flanders are barge transport related.[6]

Table 10 shows emission factors per tonkilometer for canal construction for the relevant canals.

3.4.2. Waterway infrastructure maintenance and operation

This component comprises emissions linked to maintenance and operation of waterway infrastructure. These emissions occur both on natural and artificial waterways. Again, two approaches can be proposed: starting from the ecoinvent process “maintenance, operation, canal” or linking specific data related to materials, transport and energy used in maintenance and operation of specific canals to relevant ecoinvent subprocesses (such as “gravel, unspecified, at mine”, “brick, at plant”, “roundwood, azobe”, and “electricity mix”). Specific waterway maintenance and operation data were only available for one M2 type canal (canal Leuven-Dijle), allowing a detailed calculation. Due to unavailability of such data for other waterways however, the first approach was applied to the other waterways.

Ecoinvent process “maintenance, operation, canal” inventory is again based on values for Main-Donau canal and includes electricity consumption due to operation of watergates. Also land occupation and transformation are taken into account.[7] The main resource consumed is electricity (3,42 kWh per meter*year). Emissions linked to maintenance and operation of 1 m*year of canal are presented in Table 3. Total maintenance emissions for a specific canal on a yearly basis require multiplying with canal length.

Applying the same approach as with canal construction, using specific waterway demand on the selected waterways and assigning 45% of emissions to barge transport, emissions per tonkilometer can be calculated for waterway maintenance and operation (Table 11). Since operation and maintenance are required on all canals, the related emissions are relevant for all selected canals, including older ones.

4. Results

Based on above calculations, the relative importance of different transport service components for IWW can be analyzed for different pollutants, per barge type and per waterway. This provides a much more detailed understanding of the importance of different pollutants in the case of IWW transport, and also allows to demonstrate the weight of each of the components for different pollutants. Also impact of barge type and waterway size on resulting emissions over different components can be examined in this approach.

Below, three illustrative cases are presented to present the main conclusions with regards to IWW transport. In a subsequent section, the findings for IWW transport are compared with the literature findings for other transport modes.

4.1. Comparison between pollutants

This type of comparison shows the relative importance of different transport service components for a number of pollutants. In Table 12, illustrated by Fig. 2, this calculation is based on a loaded M4 type barge on the canal Brussels–Scheldt (CEMT IV) on a tonkilometer basis. This comparison can be performed for other combinations of selected barge types and waterways.

Share of barge travel related emissions for this case varies between 1,56% for CH_4 and 90,2% for NO_x. While barge travel remains by far the most important category for CO_2, CO, NO_x, $PM2_{,5}$ and PM_{10}, it is relatively less important for NMVOS, NH_3, SO_2 and CH_4. Next to barge transport, also emissions related to other categories are often not negligible. E.g, for CO_2, share of non-barge travel related emissions is responsible for more than 30% of emissions, with precombustion and canal construction taking up the largest parts. Precombustion related emissions are also very significant for CH_4, SO_2 and NMVOC, where this component is even more important than barge travel related emissions. Also for NH_3 and PM precombustion related emissions are important and non-negligible. Barge manufacturing and maintenance related emissions are generally relatively small, except for NMVOC. Canal construction is particularly important for NH_3 emissions. Also for CO, CH_4 and PM_{10} the effect of emissions related to canal construction is relevant and non-negligible. Share of infrastructure operation and maintenance related emissions is relatively very small for all pollutants, ranging from almost zero (0,03% for NMVOC) to 0,59% (for CH_4).

[5] Although this canal is only 20 km long, it is of large economoc importance, as it connects the port of Brussels to the seaport of Antwerp, and thus links the two largest cities of Belgium.

[6] An increase in barge transportation would increase the 45% portion, however the other functions are also not constant (e.g. water management is also becoming more important with regards to flood control linked to climate change effects) which makes it difficult to forecast this evolution.

[7] Dredging is not taken into account in ecoinvent. As dredging activities can differ substantially between specific waterways, this might be a significant underestimation of waterway infrastructure maintenance related emissions on certain waterways. Taking this into account would therefore require a differentiated analysis of dredging activities per canal, which was however outside the scope of this study.

Table 12
Emission factors for different components in g/tkm for M4 barge on CEMT IV canal Brussels–Scheldt.

	Barge operation		Barge fleet		Transport infrastructure		
	Barge travel	Precombustion	Barge manufacturing	Barge maintenance	Canal Construction	Infrastructure operation & maintenance	Total emission (g/tkm)
NH_3	1,18E−04	1,73E−04	3,94E−05	2,72E−05	2,36E−04	2,68E−06	5,96E−04
SO_2	2,36E−02	1,02E−01	3,76E−03	6,25E−04	5,96E−03	6,29E−04	1,36E−01
CO_2	3,69E+01	1,08E+01	9,67E−01	1,39E−01	6,07E+00	1,97E−01	5,51E+01
CO	1,02E−01	1,68E−02	8,21E−03	1,99E−04	2,55E−02	6,09E−05	1,53E−01
NO_x	5,26E−01	4,09E−02	1,93E−03	3,87E−04	1,33E−02	3,24E−04	5,83E−01
CH_4	8,73E−04	4,44E−02	1,98E−03	4,03E−04	7,98E−03	3,31E−04	5,60E−02
NMVOS	2,09E−02	2,82E−02	1,56E−03	1,81E−02	2,04E−03	2,46E−05	7,09E−02
$PM_{2,5}$	1,65E−02	3,99E−03	5,58E−04	2,73E−05	1,40E−03	4,79E−05	2,25E−02
PM_{10}	1,74E−02	5,20E−03	1,54E−03	9,64E−05	4,20E−03	5,98E−05	2,85E−02

4.2. Comparison between barge types

In addition to the above comparison between pollutants, it is also interesting to look at how the relative share of different components varies per barge type for a particular pollutant on a specific waterway. To illustrate this type of comparison, Fig. 3 shows the relative importance of different components per loaded barge type on the canal Brussels–Scheldt for CO_2 emissions on a tonkilometer basis. This comparison can of course also be performed for other combinations of pollutants and waterways.

The figure indicates that (except for M1 and M2), the larger the barge type considered, the larger the relative share of emission related to vehicle fleet and waterway infrastructure becomes, and the lower the relative share of emissions related to vehicle operation. Indeed, comparing an M3 barge to an M8 barge, the share of barge travel is found to decrease from 67,2% to 55,4% and that of precombustion from 19,7% to 16,2%, while the share of barge fleet related emissions increases from 2,0% to 4,3% and that of waterway infrastructure from 11,2% to 24,1%. However it should be stressed that these are changes in relative terms: over the range of barge types, total emissions expressed in tonkilometer decrease significantly in absolute terms when ship size increases: from 56,1 g CO_2/tkm for M3 barge to 26,0 g CO_2/tkm for M8 barge, due to the scale effects in barge operation.

It is important to stress that these results are sensitive to two important assumptions. First, load rate is only differentiated per waterway, but considered constant for all barge types on that specific waterway. Secondly, emission factors related to barge fleet (barge maintenance & barge manufacturing) expressed per tonkilometer are considered constant over different barge types due to a lack of transport performance data over life-time per barge type, although one might expect that economies of scale would actually also play a role here.

The same type of analysis can be applied to other pollutants and per different waterway class.

4.3. Comparison between waterways

This third type of analysis assesses how the relative share of different components varies per waterway type for a particular pollutant and a particular barge type. As an example, Fig. 4 illustrates a comparison of waterways, showing the relative importance of different components for NH_3 on these different waterways using a loaded M4 type barge (except for canal Leuven-Dijle where a M2 barge is considered, since larger types are not allowed on this waterway), on a tonkilometer basis. Here comparisons of other combinations of pollutants and barge types are of course possible.

The share of barge operation related NH3 emissions (between 48,9% for canal Brussels–Scheldt and 79,3% for canal Bruges–Ghent) is relatively small compared to the share of barge operation related CO_2-emissions (see Fig. 4), which means that other components have a relatively large share in NH_3 emissions. For smaller canals, emissions related to canal construction are assumed to be negligible due to the fact that these canals have been excavated centuries ago. For larger, more recent canals, share of NH_3 emissions is however significant, ranging between 28,1% for Albert canal and 39,5% for canal Brussels–Scheldt. On the other hand, emissions related to operation and maintenance of waterway infrastructure are relatively larger for smaller waterways, due to limited economies of scale on these waterways and thus higher specific canal demand. This last effect does not fully compensate large

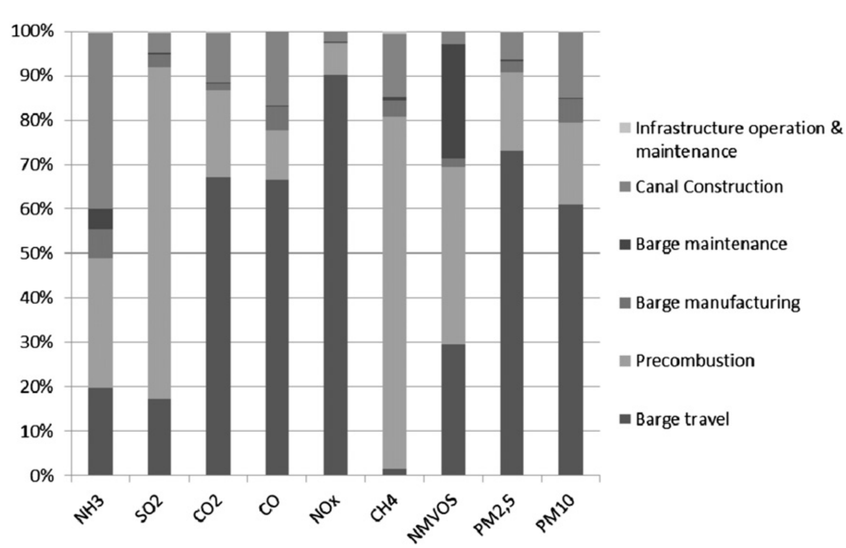

Fig. 2. Relative importance of transport service components for different pollutants: M4 barge on CEMT-VI type canal (ton kilometer basis).

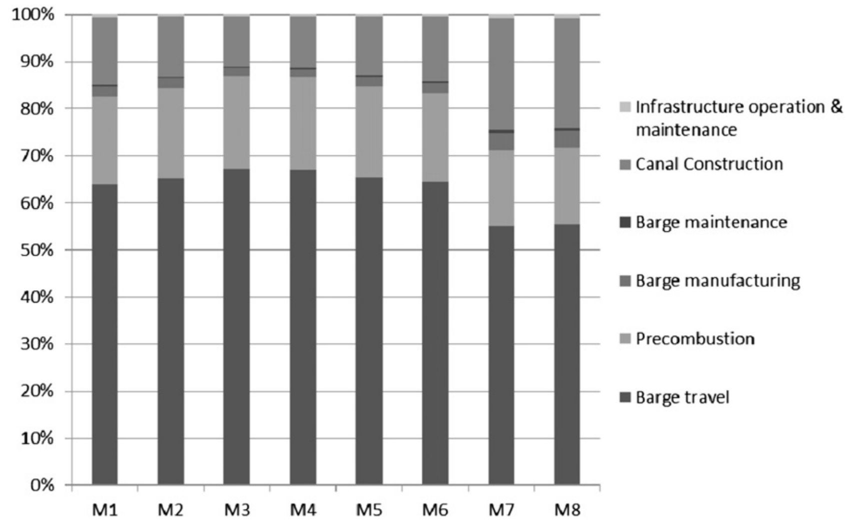

Fig. 3. Relative importance of transport service components per loaded barge type on CEMT VI type canal: CO2 emissions (ton kilometer basis).

canal construction related NH_3 emissions for larger more recent canals, so that total NH_3 emissions are largest for canal Brussels–Scheldt (5,96E−04 gNH_3/tkm) and Albert canal (4,27E−04 gNH_3/tkm), and lower for smaller canals (between 3,10E−04 gNH3/tkm for canal Roeselare–Leie and 3,44E−04 gNH_3/tkm for canal Ghent–Bruges). Obviously, rivers have no canal construction related emissions and thus lower total values (2,11E−04 gNH_3/tkm for Upper Scheldt).

4.4. Validation of results and comparison with other transport modes

As already indicated in the literature review, the amount of published LCA studies on freight transport modes is limited. In addition, as with passenger transport, LCA comparisons between transport modes have to be approached carefully. For example, in his report to develop a methodology to account for the infrastructure of high-speed passenger traffic, Tuchschmid (2009) explicitly made no comparison to other transport modes, as in his opinion such a comparison would require more country specific data about topography and more analysis on the typical lifespan of traffic infrastructure against the transported goods and passengers, and should include the maintenance of traffic infrastructure (which was excluded in his study).

Therefore, a scientifically solid comparison of transport modes from an LCA perspective in the context of our study would require applying the same methodology described in this paper on the road and rail transport sector in Flanders, and is thus ground for further research. However, a prudent preliminary comparison with findings of other studies might already give some potential first insight with regards to order of magnitudes. The study of Spielmann and Scholz (2005) which compares road, rail and water transport emissions based on ecoinvent data looks particularly interesting to validate our region specific findings, however their results are illustrated using normalized emission scores (where one transport service is selected as the reference service with calculated cumulative emissions set at 100% and expressing the emissions of other transport services as percentages in relation to the reference transport service), and therefore does not allow comparison with our emission values per tonkilometer. It does however allow to compare the relative shares of the different transport components for IWW for certain pollutants. Barge travel and pre combustion account for 95% of NO_x, and for around 85% of CO_2 emissions according to Spielmann and Scholz, which seems to be in line with the relative shares in our calculations, with the exception of the lower shares for larger ship types (M7 and M8) in our calculations. However, for $PM_{2.5}$ and definitely for PM_{10}, the low relative shares published by Spielmann and Scholz for barge operation (around 57% and only 5% respectively) are strongly diverging from our findings which suggest relative shares of barge operation of respectively 91% for $PM_{2.5}$ and 79% for PM_{10} emissions by a M4 barge on a CEMT VI type canal. Our findings for barge travel related emissions are, however, in the same order of magnitude as those published by den Boer, Brouwer, and van Essen (2008) for PM_{10}, and den Boer et al. (2011) for $PM_{2.5}$.[8] IWW is also not scoring particularly well for operational PM emissions compared to other transport modes according to den Boer et al. (2008; 2011), which contradicts findings of Spielmann and Scholz (2005). In our opinion, infrastructure related PM emissions in Spielmann & Scholz are therefore potentially overestimated. However, we would like to add that the operational share of PM emissions is expected to decrease significantly in the future, due to the 10 ppm sulfur standard for IWW diesel in place from 2011, and the introduction of Phase IV legislation through Directive 2012/46/EU which relates to measures against the emission of gaseous and particulate pollutants from internal combustion engines to be installed in non-road mobile machinery. It is e.g. expected that by 2020 operational $PM_{2.5}$ emissions will drop by 28% for the average barge fleet (den Boer et al., 2011). This will evidently raise the relative share of infrastructure related PM emissions for IWW.

Comparison of our findings for IWW transport with other transport modes based on the findings of Facanha and Horvath (2007) is even less straightforward, as their study uses a different methodology (hybrid LCA, using a combination of process-based LCA and input–output analysis-based LCA) in a different geographical context (US) on other transport modes (road, rail and air transportation) on a ton-mile basis. As they do not include IWW transport, it is impossible to assess if values based on their methodology are in the same order of magnitude as our results for the same transport mode; but recalculating values of Facanha and Horvath to a tonkilometer basis gives values of 24,85 g CO_2 per tonkilometer for intermodal rail (with payload of 2.093 t) and 116,20 g CO_2 per tonkilometer for road transport (with payload of 12,5 t), which is respectively 54% lower and 111% higher than the value in Table 12 for an M4 barge on a CEMT IV canal. For NO_x, values of 0,46 g NO_x per tonkilometer for intermodal rail and 1,60 g NO_x per tonkilometer for road transport are respectively 21% lower and 174% higher. For SO_2, values of 0,063 g SO_2 per tonkilometer for intermodal

[8] For example: $PM_{2.5}$ tank-to-wheel emissions for M6 barge on CEMT VI waterway: 0,013 g/tkm in den Boer et al. (2011) versus 0,012 g/tkm in our calculations; PM_{10} tank-to-wheel emissions for M6 barge on CEMT VI waterway: 0,020 g/tkm in den Boer et al. (2008) versus 0,013 g/tkm in our calculations. This lower value for PM_{10} can be explained through the more recent nature of the EMMOSS emission data, as well as a difference in loading rate.

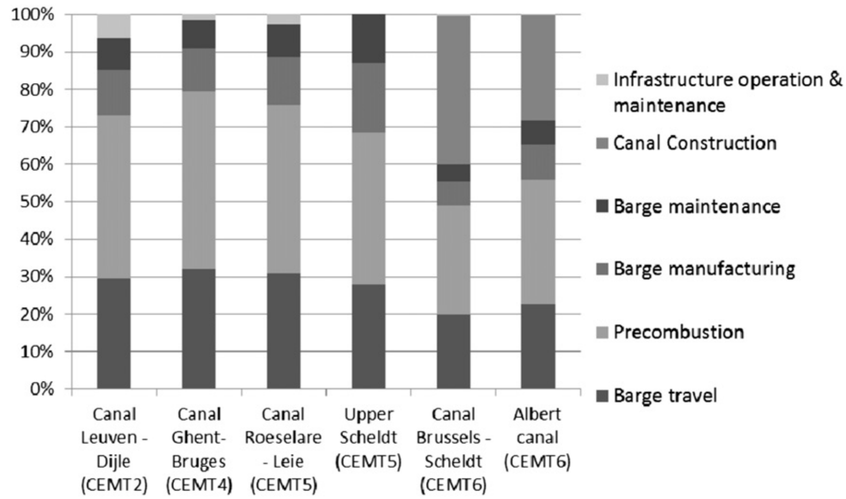

Fig. 4. Relative importance of transport service components for NH_3 on different waterways using loaded M4 type barge (ton kilometer basis).

rail and 0,093 g SO_2 per tonkilometer for road transport are respectively 53% lower and 31% lower. Although we stress that this comparison should be looked at with caution taking above remarks into account, it seems to indicate that intermodal train is scoring better than IWW transport on these criteria, whereas IWW is scoring significantly better than road transport on most criteria, but also worse for some specific pollutants such as SO_2. However, confirmation of these findings would require applying the same LCA methodology in our study on rail and road transport in Flanders.

5. Discussion and conclusions

This paper applied an LCA based methodology in order to determine the relative share of different transport service components (i.e. vehicle travel, precombustion, vehicle construction, vehicle maintenance, infrastructure construction and infrastructure maintenance) on total cumulative emissions for barge transport. Taking into account these different components allows assessing environmental sustainability of a transport service with regard to emissions in much more detail.

In this paper emission factors recalculated from outputs of the EMMOSS model were combined with ecoinvent data for relevant processes, in order to map barge related emissions in Flanders for a range of pollutants. For most pollutants, vehicle operation related emissions remain the most important category, however for some of these pollutants (e.g. SO_2 and CH_4) precombustion related emissions were found to be more important than vehicle travel related emissions. For some pollutants (NH_3, TSP, VOS en NMVOS), barge fleet and waterway infrastructure related emissions play a relatively large role in the cumulative emissions. For most pollutants however this share is relatively modest (between 10% and 20% for CO_2, CO and PM_{10}) or even relatively small (below 10% for SO_2, NOX and $PM_{2,5}$) for average conditions. But the analysis also showed that on a particular waterway, relative share of different components in pollutant emissions can vary significantly with barge type. In addition, for a particular barge type relative shares can vary strongly depending on the waterway considered (e.g. emissions related to canal construction are only relevant for more recently built artificial waterways). Drawing generalized conclusions on relative shares of different components and on total level of emissions is therefore not straightforward.

In a next phase, the methodology could be improved by employing a more refined approach using specific data related to materials, transport and energy used in barge fleet and waterway infrastructure construction and maintenance, and applying emission factors of relevant ecoinvent subprocesses. This requires filling data gaps with regard to both barge and waterway infrastructure and maintenance data, and this per barge and waterway type. Also data on load rates per barge type as well as data on transport performance of barges over their lifetime per barge type would allow further refinement in calculations.

Next, impact assessment phase and interpretation phase of LCA should be performed in order to determine severity of polluting effects. Impact of emitted pollutants will largely depend on the number and demography of people exposed. For more locally dispersed air pollutants such as particulate matter, this requires mapping receptor density in the neighborhood of waterways in Flanders.

Additionally, in order to allow a comparison of environmental sustainability of different transport options in specific cases, the methodology should be applied to other transport modes as well.

It should be stressed that such an LCA based approach will become even more important in the future, since improvements in engine technology and emission lowering technologies might further reduce the relative importance of direct vehicle-travel related emissions compared to vehicle and infrastructure related emissions.

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